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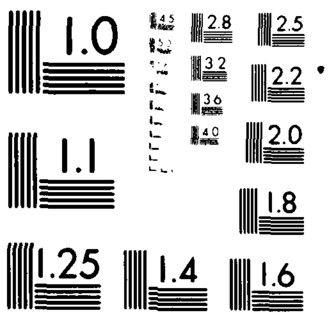

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REPORT DAAK70-79-C-0138

MANUFACTURING METHODS AND TECHNOLOGY FOR PRODUCTION HOT FORGING OF ALKALI HALIDE LENSES

Honeywell Inc.
Ceramics Center
1885 Douglas Drive
Golden Valley, MN 55422

30 JUNE 1980

Semiannual Report No. 1
7 September 1979 - 7 April 1980

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Prepared for
USAECOM NIGHT VISION AND ELECTRO OPTIC LABORATORY
Fort Belvoir, VA

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The forged-to-shape process has been examined and optimized. The original process demonstrated the feasibility of forging alkali halide single crystals into lenses without the use of conventional lens polishing and figuring techniques. The process had not been optimized with respect to cost or quantity production. In the first portion of this program, the process has been examined and refined. The new process is now in a form which can be readily applied to a production environment.

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FIRST SEMIANNUAL REPORT

CONTRACT NO:	DAAK70-79-C-0138 Manufacturing Methods and Technology for Production Hot Forging of Alkali Halide Lenses
PERIOD COVERED:	7 September 1979 - 7 April 1980
WRITTEN BY:	Regis J. Betsch, Sr. Development Engineer
PROGRAM MANAGER:	William B. Harrison, Supervisor, Optical Development

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ABSTRACT

The forged-to-shape process has been examined and optimized. The original process demonstrated the feasibility of forging alkali halide single crystals into lenses without the use of conventional lens polishing and figuring techniques. The process had not been optimized with respect to cost or quantity production. In the first portion of this program, the process has been examined and refined. The new process is now in a form which can be readily applied to a production environment.

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PURPOSE

This project is intended to optimize the manufacturing process and techniques to produce alkali-halide IR lenses by the hot forge-to-shape process. This process was developed at the Honeywell Corporate Materials Science Center under Contract DAAK70-77-C-0218 sponsored by Defense Advanced Research Projects Agency and USAECOM Night Vision and Electro Optics Laboratory. The manufacturing techniques under development are intended to be applied to the large family of alkali halide IR materials and in general to any other materials which are easily deformed at moderate temperatures.

The particular lens under development is a plano-concave KBr lens designed to replace the ZnSe color corrector lens in the common module IR imager, SU-103/UA. The common module is used in several Forward Looking Infrared (FLIR) systems designed to operate in the 8-12 micron wavelength region.

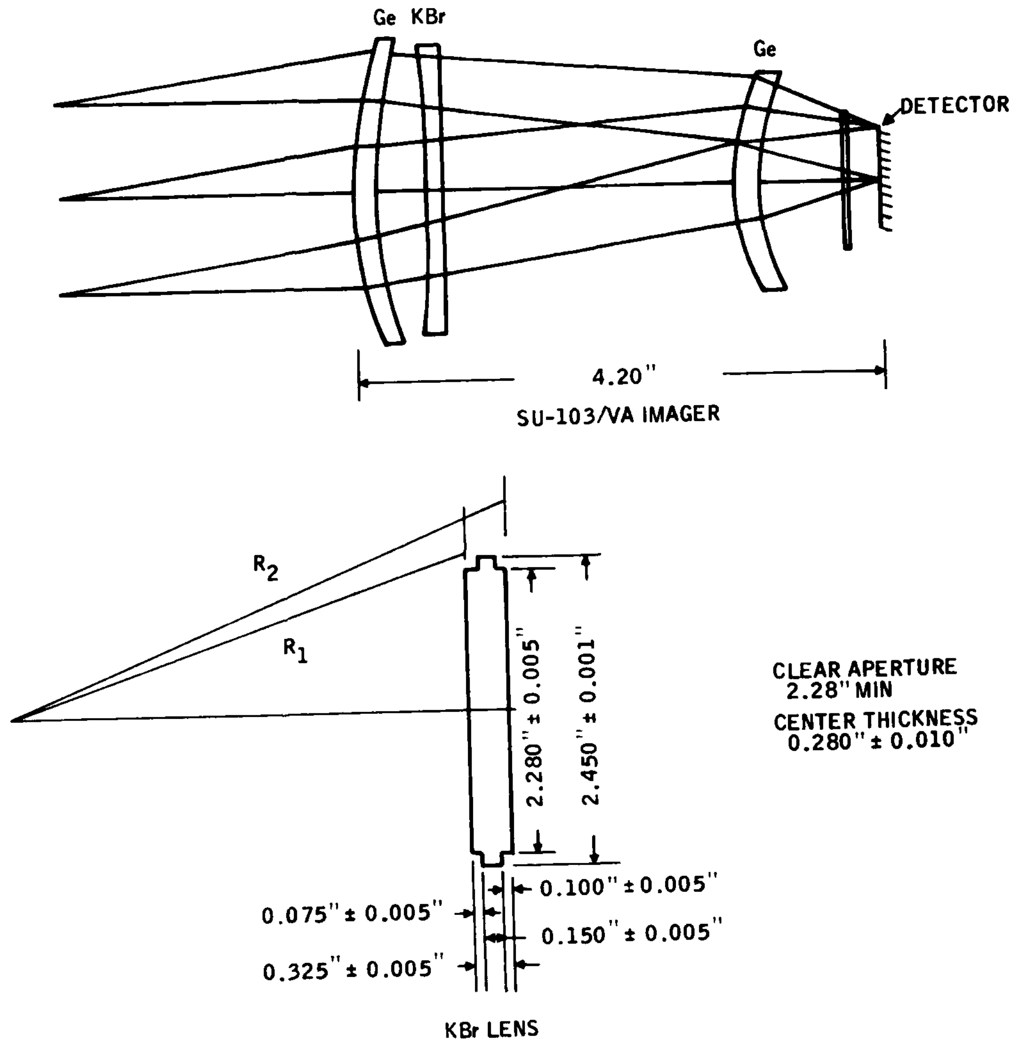
The main tasks in the program are designed to develop and document the production and evaluation processes necessary for a manufacturing environment capable to produce a minimum of 300 lenses per month. Throughout the program several deliveries of lenses are to be made totaling approximately 50 lenses. The major output of the program is to produce the complete description of the developed process and to demonstrate the capabilities of the process.

SECTION I
ENGINEERING APPROACH

1.1 INTRODUCTION

The goal of the Manufacturing Methods & Technology program is to develop the capacity to produce a minimum of 300 forged IR lenses per month. The work involves three main areas. First, the forging process inherited from Honeywell Corporate Materials Science Center (CMSC) is to be refined and made compatible to a production environment. Second, production evaluation procedures are to be generated to control incoming material and to test the forged lenses. Third, the manufacturing of hot forged-to-shape lenses requires the development of specialized production equipment. At the time this report was written, the major portion of the process refinement had been completed. The major effort is presently focused on the equipment development.

The particular lens under development is a plano-convex KBr lens. This lens is intended to replace the ZnSe color correcting lens in the SU-103/UA, common module IR imager. The dimensions of the lens are 2.45 inches in diameter and 0.28 inch center thickness. The lens has a 0.15 inch thick flange and a clear aperture of 2.28 inches. The radius of curvature of the concave side is 17.25 inches. With the KBr lens in the imager the imager specifications are: %MTF on axis 74%, %MTF off axis 66%, flange focal length (FFL) 17.86± .25mm, and effective focal length (EFL) 67.8± .7mm. The lens and the optic layout of the imager are shown in Figure 1.



	RADII	SURFACE QUALITY
R_1	17.25" ± 0.25"	80/50
R_2	∞	80/50

Figure 1. Diagram of the SU-103/UA IR Imager and the KBr Lens

1.2 REFINEMENT OF THE FORGING PROCESS

The hot forge-to-shape process for KBr lenses, which was transferred from CMSC, consisted of techniques which were in part best effort and historical in nature. The initial experience was with forging of large IR windows. In that program it was discovered that a large restraining hoop was necessary to forge crack-free plates. The restraining rings were the initial justification for using 4,000 psi helium gas in the second stage forging process. Recently, it has been found that 100 psi helium is sufficient, and possibly no helium may be needed at all. This is one example of a major process parameter which was investigated and changed to simplify the equipment design. Wishing to use the simplest forging conditions to generate the best lenses, a critical examination has been made of the forging process.

The present forging process is shown in Figure 2. The major difference between this process and the one used in CMSC is the elimination of a maching step which preceded the 2nd stage forging. The need for this step was eliminated by the use of conical dies in the 1st stage forging, which gives a properly shaped blank for the next step.

The forging process is one of conflicting parameters. The ideal lens should be both optically perfect and of a reasonable mechanical strength. The forging process was originally developed to strengthen alkali-halide windows for lasers. As a secondary effect, forging produces large residual strains within the material. In the new forge-to-shape process, this strain causes a rebounding of the lens as the pressure is removed from the dies. Optical evaluation has shown that both large residual strains and strains aligned over large areas can distinctly degrade lens quality.

The mechanical strengthening by forging is the major cause of the residual strain, and thus a compromise between the optical criteria and the mechanical strengthening must be made. This is not the case. Mechanical strengthening requires the generation of an evenly fine grained polycrystalline material through forging. However, the residual strain produced by forging is not desired for strength and, if large, the strain will make the piece much more susceptable to thermal shock. This is evident from basic materials criteria and is analogous to the strain problems in silicate glasses. Thus as a general rule, minimizing residual strain is desirable as long as the polycrystalline fine grained structure of the forging is not lost.

The refinement of the forging process has proceeded with two goals: bettering the optical quality of the lenses, and simplifying the overall process. The techniques for determining the optical quality are discussed in detail in Section 1.3. In general, residual strain has been used as a first order parameter to determine a qualitative measure of forging quality.

The simplification of the forging process has proceeded with the lowering of cost as the primary impetus. This has been accomplished by eliminating steps, reducing the complexity of remaining steps, and implementing techniques which make optimum use of equipment to reduce processing time.

The forging process is delineated for a single lens forging in Figure 2. This figure divides the forging process into four steps. The initial material inspection, the first stage forging, the second stage forging, and the final processing. The following subsections give a complete description of the forging processes and the considerations used to refine them.

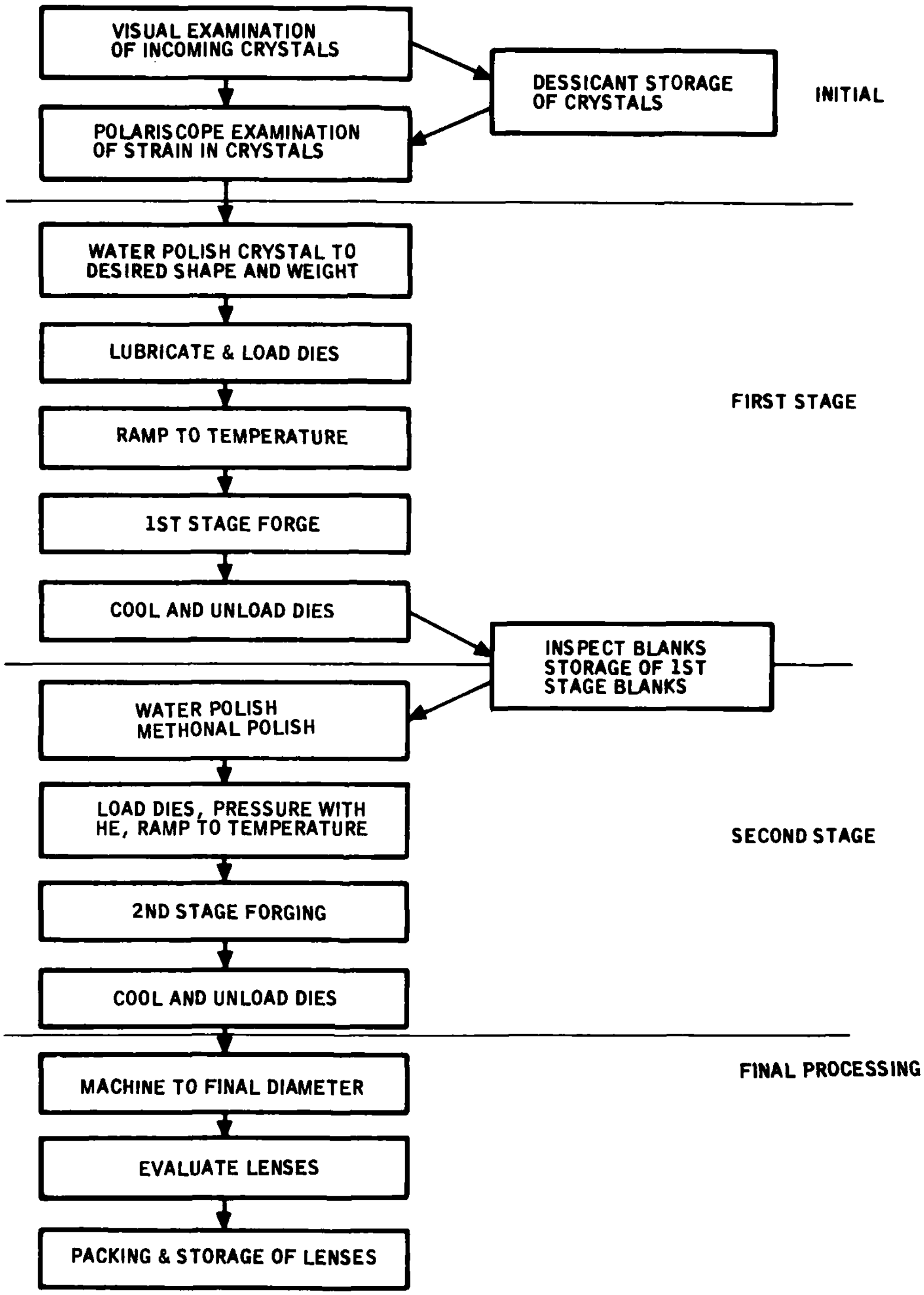


Figure 2. Block Diagram of the Forging Process

1.2.1 Initial Inspection

The KBr is purchased as single crystal cylinder (figure 3) with both the height and diameter equal to 3.8 cm (1.5 inches) and a mass of approximately 130 gms. The crystals are unpacked and visually examined for chips and cracks. The inspected crystals are then loaded onto trays along with the packing slip for identification and placed into a desiccated storage bin. Presently polariscope data is recorded for each crystal, but in a production environment one would expect to examine all the samples from one shipment and then only photograph representative samples of high and low strain crystals. Examples of low and high strain crystals as viewed with the polariscope are shown in Figure 3.

It appears that the amount of strain in the final lens is greatly determined by the amount of strain found in the starting crystals. If the initial strain levels are discovered to be too high; it will be necessary to consider the use of an annealing step at this point of the process.

As the refinement of the process continues, the starting configuration of the single crystal may change in shape and even more probably in weight. The finished lens only weighs approximately 65 grams. This is half the starting weight. It is easily envisioned that small changes in the process may allow decreasing of the starting weight of the crystals. The present materials cost for the 130 grams KBr crystals is $40.00, with the weight being a major factor in cost.

High Strain Crystal   Low Strain Crystal

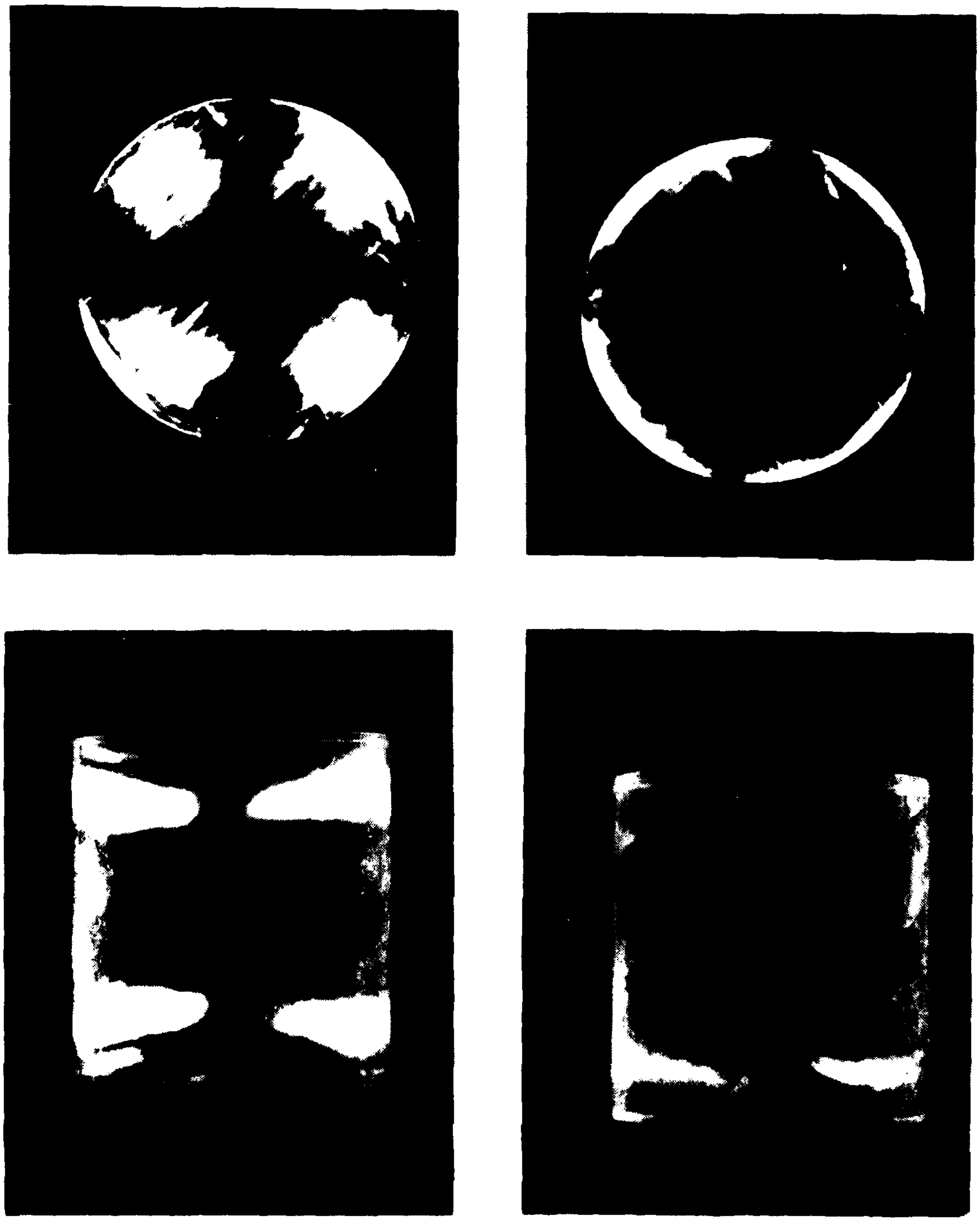


Figure 3. Polariscope Photographs of High and Low Strain KBr Crystals as Received from Supplier

1.2.2 First Stage Forging

The first stage forging step is probably the most critical. The major reduction in thickness occurs during this step, making it the greatest potential source of residual strain. Changing any part of the first stage process may easily force changes throughout the rest of the forging steps. Because of this, the major emphasis has been in defining the "best" set of parameters for the first stage process.

The first stage forging process consists of five steps as outlined in Figure 2.

First stage forging step involves producing a slight cone on both ends of the crystal cylinder and rounding the edges (Figure 4). The conical shape eliminates the problem of trapped air between the die and the KBr. Rounded corners were found to be necessary since sharp edges tend to fold over at the edges producing channels into the forging's edges.

The shaped crystal is approximately 1.4 inches high x 1.4 inches diameter and weighs about 92 grams oriented with the <100> axis parallel to the forging direction. The <100> orientation has proven to be an acceptable if not the best forging direction. The starting aspect ratio is not a well defined parameter, but the 1.0 ratio appears to give satisfactory and reproducible results.

At this stage, the crystal has had about 38 grams of material removed. Recent attempts at using smaller starting crystals shows that only a 10 grams removal of material is needed to shape the crystal. Thus, it appears that 105 grams of starting-crystal mass may be all that is necessary.

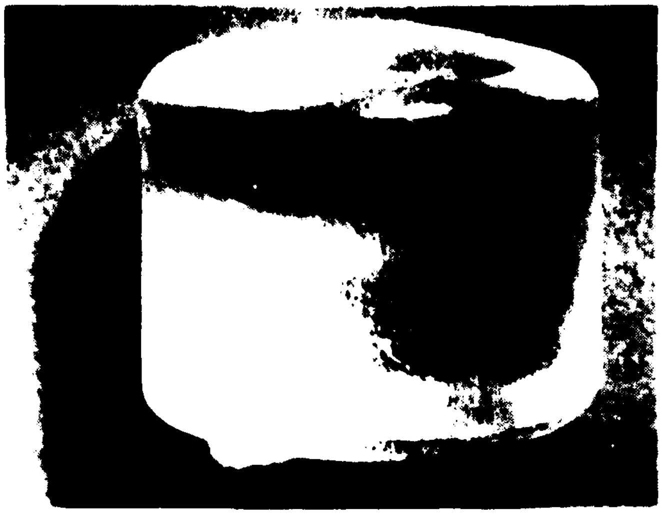


Figure 4. Water Polished KBr Crystal Prepared for First Stage Forging

During this study it was observed that the KBr cylinders did not deform uniformly during forging. There are four directions which allow easier plastic flow of the material perpendicular to the <100> forging axis. This results in the forging acquiring an almost square projection normal to the die motion direction during forging. When the corners of this square make contact with the restraining sleeve, the material is forced to flow along the difficult plastic deformation directions (i.e. normal to the edge of the square) until uniform contact is made at the restraining sleeve. A cleaved <100> cube was partially forged to verify the direction of easiest plastic deformation. The deformation of the sample (Figure 5) distinctly shows that easy direction is 45° to the <100> faces, thus it is along the <110> direction. This data suggests a simple but elegant technique to reduce the amount of residual strain due to first stage forging. Cubes have been ordered with x, y || <110> and z || <100>. This configuration retains the <100> forge direction while using a shape which allows less movement of the KBr along the hard deformation direction (i.e. the cube's corners). Forgings will be made to investigate the possibility that this crystal configuration will lead to reduced residual strain within the material.

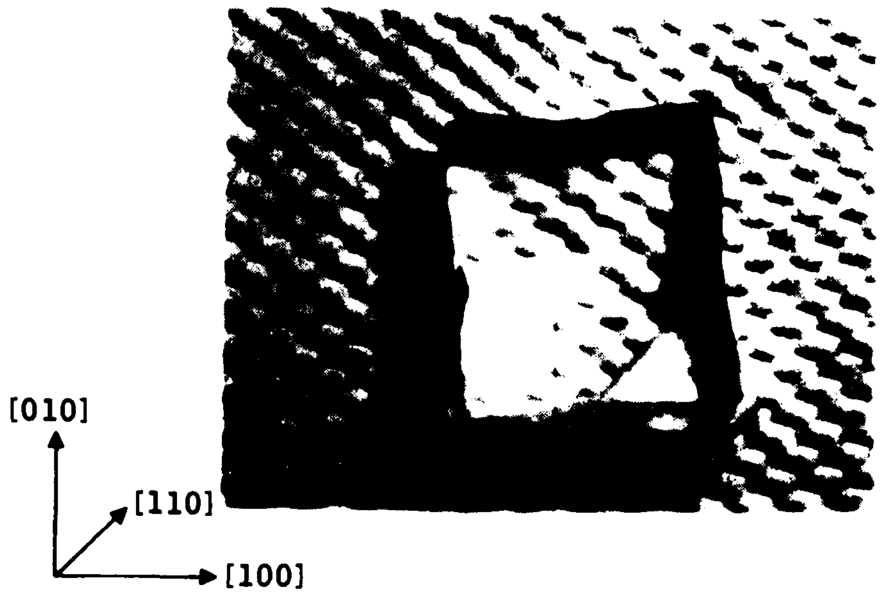


Figure 5. Forged Cube of KBr Demonstrating Hard and Soft Plastic Flow Directions

The second step in the first stage forging process (Figure 2) is the lubrication and loading of the dies. The choice of lubrication of shaped dies proved to be less than obvious. Sheet Teflon, successfully used with flat dies, tended to bunch up and cause a considerable amount of relief in the surface of the first stage forging. This required a machining step to be performed prior to second stage forging. This was self-defeating since shaped dies were intended to remove this machining step which was necessary for forgings produced between flat dies. Silicone oil, which was the first choice of substitute lubricant, produced very highly strained material. Also, there is a major concern that Silicone oil remaining on the lens surface would affect subsequent coating processes.

The next choice was to attempt to remove the lubrication completely. It was shown that, for both polished and fine sanded dies, the examined metal-dies all showed adhesion to the KBr forging. The metals studies included: 420-F stainless, 4140 tool steel, and brass.

The solution was found in a fluorocarbon mold-release spray MS-122 (Miller Stephenson). This spray is stable at 250°C and is inert when in contact with the 420-F stainless dies. It was found that MS-122 does react chemically with brass at 250°C, but does not affect the forging when using a brass sleeve.

The MS-122 has proven to give the best forging results to date. Also, since it is suitable for use with shaped dies, it has allowed the elimination of the second stage pre-machining step.

The next step in the first stage forging process (Figure 2) is the ramping to temperature. The present technique is to lubricate and load cold dies with the prepared crystals at room temperature. The loaded dies are placed on the forging press and brought to temperature over a two hour period. This has a major disadvantage in that the press is unusable for any purpose during this time. The straightforward solution to this is preheating the loaded dies at 250°C and placing these on the heated platten. The ability to easily handle 250°C loaded die sets was demonstrated with hot-unloading experiments.

The first solution, using a preheating furnace, has the major advantage of being able to ramp to temperature independent of the state of the forging press (i.e. overnight) and also the advantage of being able to hold shaped and water polished crystals at temperature until they are used. The holding of crystals at temperature (250°C) reduces the problem of surface fogging due to moisture.

The main disadvantage of using a preheating furnace for loaded die sets is that a large number of expensive die sets is needed to produce a days supply of forgings. Also the furnace cavity necessary to hold the die sets (approximately 32 cm high by 10 cm in diameter) would be quite large. Still this solution is better than cold loading the press, and uses known techniques.

A possible second solution to the problem would be to: ramp the crystals to temperature and then hot-load the dies. Only two press loads of dies would be needed because one set would be unloaded and then loaded while the other set is in the press for a forging cycle. The major disadvantage of this solution is that there is no production experience in handling the 250°C single crystals, which can easily be thermally shocked. Investigations into this technique are being pursued to determine its feasibility.

The next step in the first stage process (Figure 2) is the actual mechanical forging. The forging is performed with conical 420-F stainless dies (4° cones) in a cold rolled steel sleeve. The final forging diameter is 7.3 cm (2.87 inches) and the forging thickness is 1.2 cm (0.47 inch) in the center and 0.7 cm (0.27 inch) at the edge.

The major parameter in the forging process is the speed at which the forging occurs. The original process used a constant ram speed of 1.25 mm/min (.05 inch/min). This ram rate was found to produce fairly low strain forgings. The forging time for a typical crystal (from a height of 3.5 cm to a height of 1.2 cm) was about 20 minutes not counting the time to slowly make contact between the press and dies.

A savings in time can be realized when a constant strain rate is used. Strain rate can be argued to be the pertinent factor determining the maximum forging speed. The strain is defined as $\Delta\ell/\ell$, where ℓ is the present length of the crystal and $\Delta\ell$ is the change in length of the crystal due to forging. The strain rate is just the amount of strain which occurs in a particular amount of time. For example, if a crystal is initially 3.5 cm long and a 10%/min strain rate is used, after one minute the crystal would be 3.5 - .35 or 3.15 cm long.

To a first approximation, the strain generated within the crystal will be proportional to the strain rate used in the first stage forging. If a 10%/min strain rate is used, then a 1 mm slice of material will decrease by .1 mm in one minute regardless of the total height of the crystal. Thus, a constant strain rate relates to the constant amount of strain imparted to a given constant volume of material per unit time. This implies that strain rate and not ram speed should be the controlled parameter during forging.

By using a 6%/min strain rate the final ram speed is .8mm/min instead of the original 1.25 mm/min originally used. The total forging time is only 17 minutes instead of 20 minutes. By using a constant strain rate the final strain rate is less than if a constant ram speed is used. This results in a lower residual strain in the forging while using less forging time.

Using a constant strain rate produces an exponential decay in ram speed. This can be seen as follows:

$$\text{Strain rate} = \frac{\Delta \ell}{\ell} \text{ Per unit time} \equiv \frac{1}{\ell}\frac{d\ell}{dt}$$

Where ℓ - The initial crystal length

$d\ell$ - The change in length

$\frac{d\ell}{dt}$ - The instantaneous ram speed

For a constant strain rate:

$$\frac{1}{\ell}\frac{d\ell}{dt} = -K \qquad \text{Where K is a constant}$$

The negative sign for "K" is used to give a positive strain as the crystal is compressed, i.e. $\Delta\ell$ negative.

Rearranging terms gives:

$$\frac{d\ell}{dt} + K\ell = \ell' + K\ell = 0 \qquad \ell' = \frac{d\ell}{dt}$$

The solution to this differential equation is:

$$\ell = Le^{-Kt} \qquad \text{and} \qquad \ell' = \frac{d\ell}{dt} = -LKe^{-Kt}$$

where L is the original length of the crystal. Thus, the ram speed, ℓ', decreases exponentially as a function of time when a constant strain rate is used.

The final step in the first stage process (Figure 2) is the ramping of temperature from 250°C to room temperature. As in the ramping to 250°C, considerable savings can be realized if this step can be performed independent of the forging press. Preliminary tests have shown that the dies can be immediately unloaded and the forgings exposed to room temperature air without any noticeable effect on the forging. This is extremely encouraging in that a cool down furnace may be unnecessary.

A compilation of the first stage parameters is given in Table 1. The table shows the parameters giving the best lenses along with the process as inherited and a list of the other possibilities which were examined.

Table I. First Stage Forging Parameters Past and Present

Parameter	Present Best Conditions	Past	
		As Inherited	Examined
Isostatic pressure	0 psi	0 psi	4 K psi He
End forging load	35,000 lb/3" forging	35,000 lb/3"	5,000 lb/3"
Temperature	250°C	250°C	275°C, 300°C
Forging direction	<100>	<100>	<110>, <111>
Input shape	Cylinder	Cylinder	Cube
Lubrication	Spray fluorcarbon	Sheet Teflon	Silicon oil, no lubrication
Aspect ratio	1.0 height/dia	1.0	.77, .60
Die shape	Conical	Flat	
Die material	420-F Stainless steel	Brass	
Sleeve material	Steel	Steel	Brass
Forging speed	6.4% Constant strain	50 mils/min	Constant strain to 50%, ram speeds of 20 & 30 mils/min
Series	1 High	1 High	1 High
Water polish	Conical ends, rounded corners	Rounded corners	No water polish

1.2.3 Second Stage Forging

The second stage forging process does not strongly affect the residual strain of the final lens. The initial strain of the single crystal and the induced strain from the first stage forging are responsible for the bulk of the strain in the final lens.

The second stage process exists mainly to forge the blank to a precise optical shape with as perfect surface finish as possible. The major concern with the process is that, as inherited, it contains several labor intensive steps. The overall process has been quite successful in reproducability of quality lenses. Thus, any changes in the process must be made with considerable care. A list of the steps involved in given in Figure 2.

The first step in the second stage forging is the water and methonal polishing. This step is necessary to remove the residual lubrication used in the first stage process. Also in this step, the forging is reduced in weight to the 84 grams necessary for the second stage process. Since the diameter of the sleeve and curvature of the dies are constant, the crystal weight determines the final thickness of the forging. The water polish step takes approximately 20 minutes per crystal. Although an extremely time consuming step, it cannot be eliminated without a major change in the overall process. Removal of excess material accounts for the majority of time consumed. To shorten the water polishing step, future development will examine the use of lighter first stage forgings. These will require removal of less material and therefore reduce polishing time.

The water polish leaves a slight haze on the forging blank. This is removed by the methonal polish. For this step, the original process required over 30 minutes per crystal. Recently a technique was developed which should allow the reduction of this step by 20 minutes. During the final water polishing, the crystal is wiped with the wet polishing chamois while being blown dry with nitrogen, a technique which nearly eliminates haze.

Potentially the total time required for the two polishing steps may be reduced to 15 minutes per lens. The major consideration given to these polishing steps is that the resulting surface finish determines the surface finish after the final forging. Any scratches or imperfections in the surface prior to forging, will remain in the final forged lens. Thus, as a minimum, the polishing steps must remove the residual first stage lubricant and any scratches or haze.

At this point in the second stage process, the forging is slightly conical with rounded edges and weighs approximately 84 grams (Figure 6).

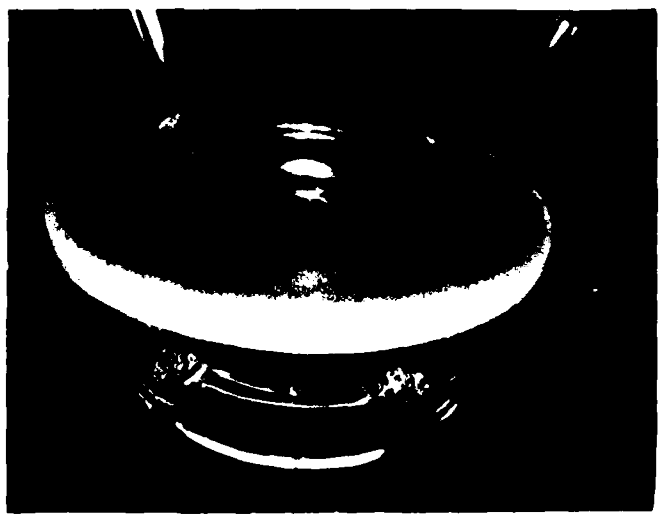


Figure 6. KBr Blank Prepared for Second Stage Forging

After the blanks are polished, they are loaded into the pyrex die sets (Figure 2). This must be performed in a dust-free environment. Any dust particles trapped between the forging and the die will leave long tracks in the final forged lens surface. This step is easily accomplished in a dust-free laminar-flow hood.

The die sets are then heated to 225^{o}C for the second stage forging. The heating presently occurs on the forge but in the future will occur in a pre-heat furnace. Again the intent is to free the press for all but actual forging.

Unlike the first stage process, it is improbable that the second stage blanks can be heated independent of the die sets. This is due to the difficulty of loading 225^{o}C blanks into dies maintaining a dust-free environment.

Once heated, the die sets are loaded into the press for forging (Figure 2). Presently the forging speed used is 0.15 mm/min. The slow forging speed was chosen to prevent surface abrasion as the forging flows along the pyrex dies. The residual strain is not affected at this speed since it is one-fifth of that used at the end of the first stage forging.

Originally 4,000 psi helium pressure was used during the final forging. It has been shown that quality lenses can now be produced using an unpressurized inert atmosphere. This has considerably relaxed the equipment design for second stage forging. Other forging possibilities previously impossible are now feasible, such as directly forging the flange into the final lens. This and other modifications are presently being investigated but it should be emphasized that the present technique produces excellent quality lenses and should be changed only after careful study.

The final step in the second stage process (Figure 2) is the cooling to room temperature. Although the present technique cools the lenses in the die sets, there is no reason that a transfer to a programmed cool down furnace cannot be used. The absolute dust-free environment required in the loading of the dies is not required during their unloading.

The final forging is an 84 gram plano-concave lens without a flange (Figure 7). Table 2 shows the second stage forging parameters giving the best lenses to date. Also listed are the original parameters and the other choices examined.

Figure 7. Second Stage Forging and the Final Lens

Table II. Second Stage Forging Parameters Past and Present

Parameters	Present	Past	
		Inherited	Examined
Isostatic	100 psi	4K psi	2K psi
End Forging Load	35,000 lb/3" lens	35,000 lb/3"	35,000 lb/3"
Temperature	225°C	225°C	
Pre-machining	None	Machine to conical shape	
Water polish	Remove fluorcarbon & 10 gms of material	Removal of damage from machining & 10 gms of material	
Methonal polish	Removal of surface haze	Removal of surface haze	
Lubrication	None	None	
Die material	Pyrex	Pyrex	
Sleeve material	Steel	Steel	
Forging speed	.006"/min	.006"/min	

1.2.4 Final Processing

The second stage lens blank is presently forged without a flange. Before mounting into the imager, the lens blank must be machined to final diameter with a flange for mounting. The final lens weighs approximately 65 grams and has a center thickness of about 6.4 mm (Figure 7). The machining step (Figure 2) may be eliminated if a flange can be directly forged during the second stage process. This would be a major cost savings because the machining is labor intensive and requires significant skills to produce a quality lens in a production environment. Machining also has the inherent problem of risking damage to the surface finish.

After the lens has been fabricated, the final mechanical dimensions of the lens can be determined to be within tolerances (Figure 1) by using standard metrological techniques.

The final step in the overall forging process is the storage of the lenses for later coating processing. The major concern is keeping the lens free from dust and moisture. This can be done by packing the lens in a sealed plastic bag with a dustless desiccant. The remaining problem is keeping the lenses scratch free. Scratches have been shown to cause major problems with coating integrity, especially in a humid environment. It would be a major advantage to the final lens production for the forged lenses to be directly transferred to the coating equipment in order to avoid dust, humidity and scratches.

1.3 OPTICAL EVALUATION TECHNIQUES

Within the scope of the MM&T program, there are three optical criteria have been measured on the KBr lenses: surface figure, transmission distortion, and the modulation transfer function (% MTF) of the lens in the SU-103/UA imager. The first two parameters measure the individual lens quality while %MTF combines the total error produced by all the lenses and the mirror alignment within the imager.

At this time several techniques are combined to determine the quality of the lenses which have been produced. Figure 8 shows the polariscope photographs of lenses 018 and 049. Notice that 018 photograph shows distinct striations in the strain and a cross pattern, neither of which are discernable in the 049 photograph. The effect of the residual strain on the surface figure (measured by Twyman-Green Figure 9) is shown in Figure 10. Note that the fringes on 018 show the overlaid form of a cross corresponding to the strain observed under the polariscope. Figure 10 also includes the double pass transmission interferograms (Figure 11) of 018 and 049. It is obvious that they are superior to the interferograms from the surface figure. This is direct evidence of the self-compensation which has been proposed to occur when mutual distortion of top and bottom surfaces occurs. For strong lenses (i.e. lenses with highly curved surfaces) the self-compensation may not work; but for this KBr lens, it appears to be a major advantage.

From figures 9 and 11, it can be safely assumed that the recent forging, 049, is superior to the earlier 018 forging. The %MTF was measured for lens 018 (Table 3) and was found to be well within specifications. Judging from figures, lens 049 is expected to be at least as good as 018 in the %MTF, if not better.

Original Process (Sample 018) | Refined Process (Sample 049)

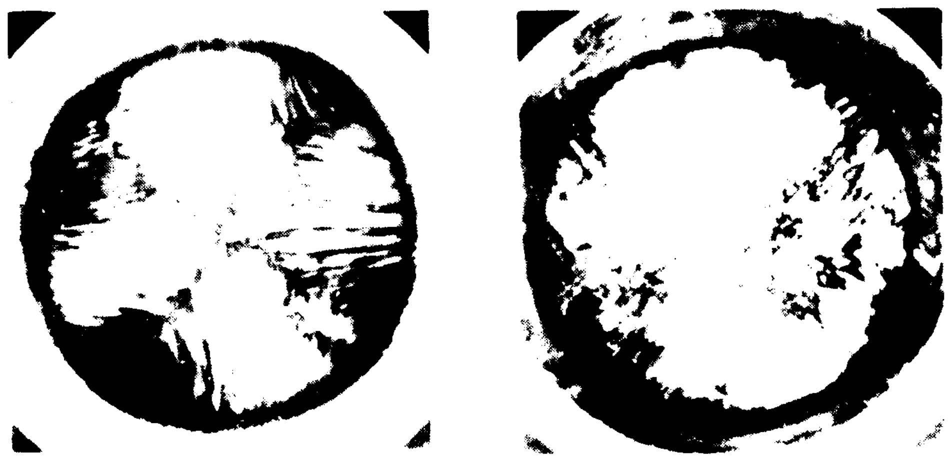


Figure 8. Polariscope Photographs of KBr Lenses as Produced by the Old and New Processes

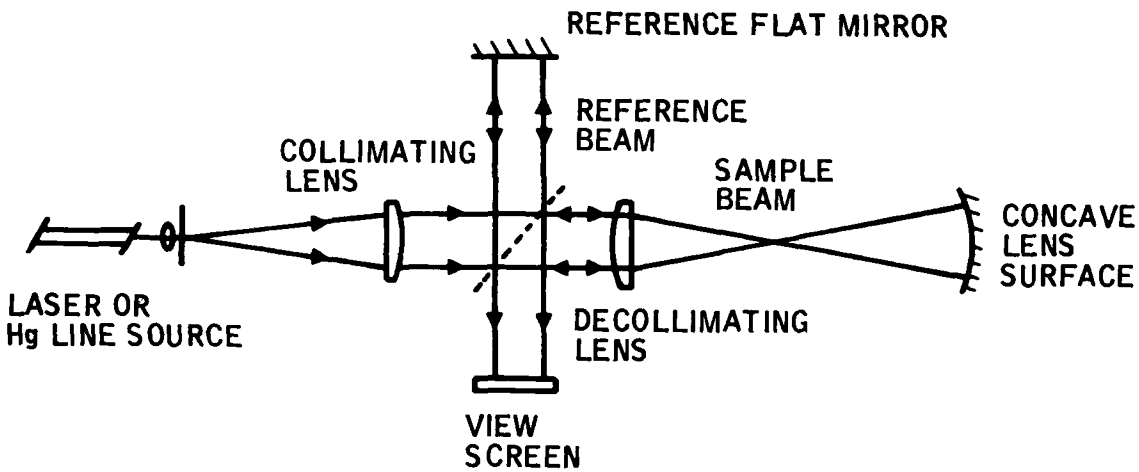


Figure 9. Diagram of the Twyman-Green Interferometer as Used to Examine Lens Surface Figure

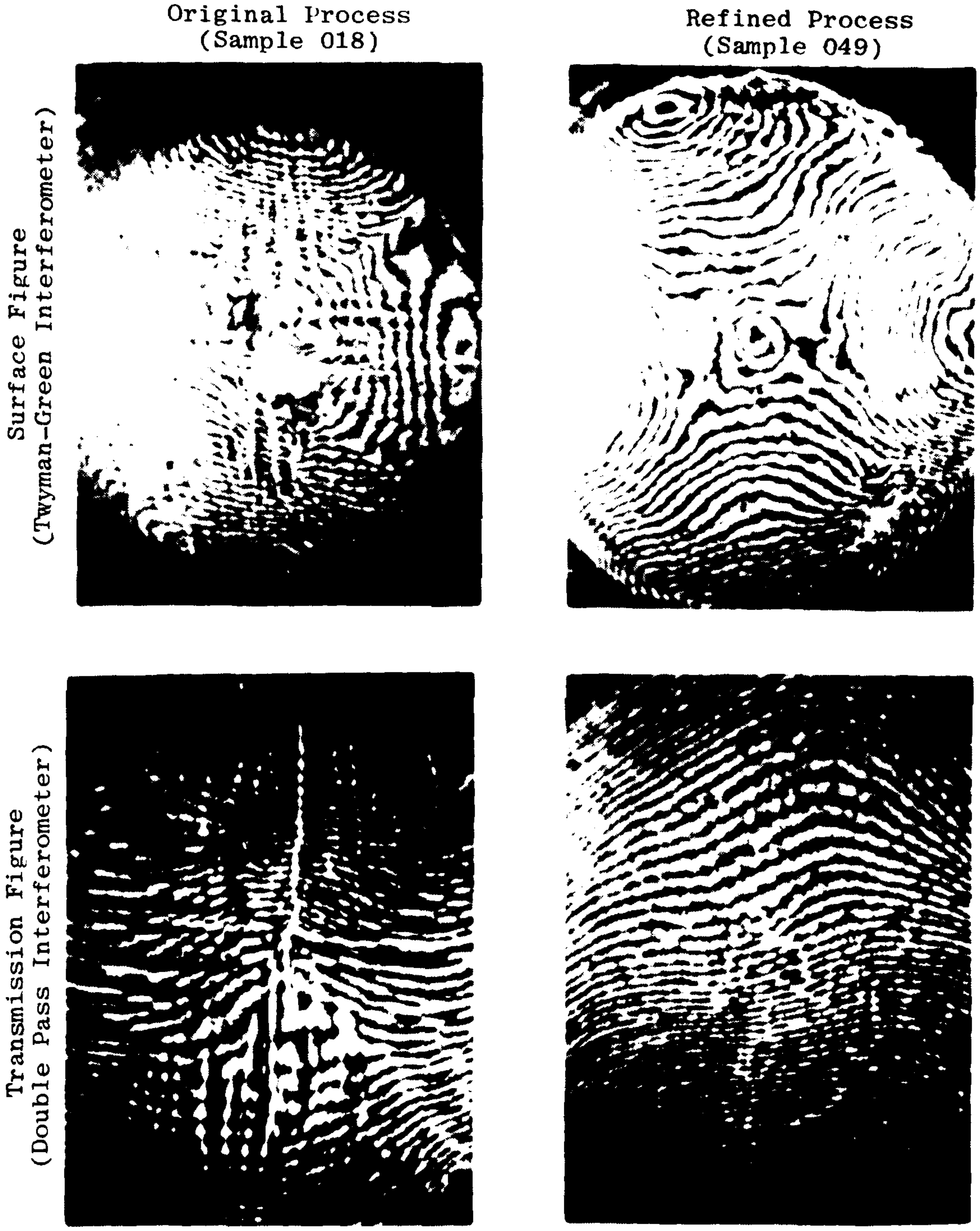


Figure 10. Sample Optical Figures of KBr Lenses as Produced Using the Old and New Processes

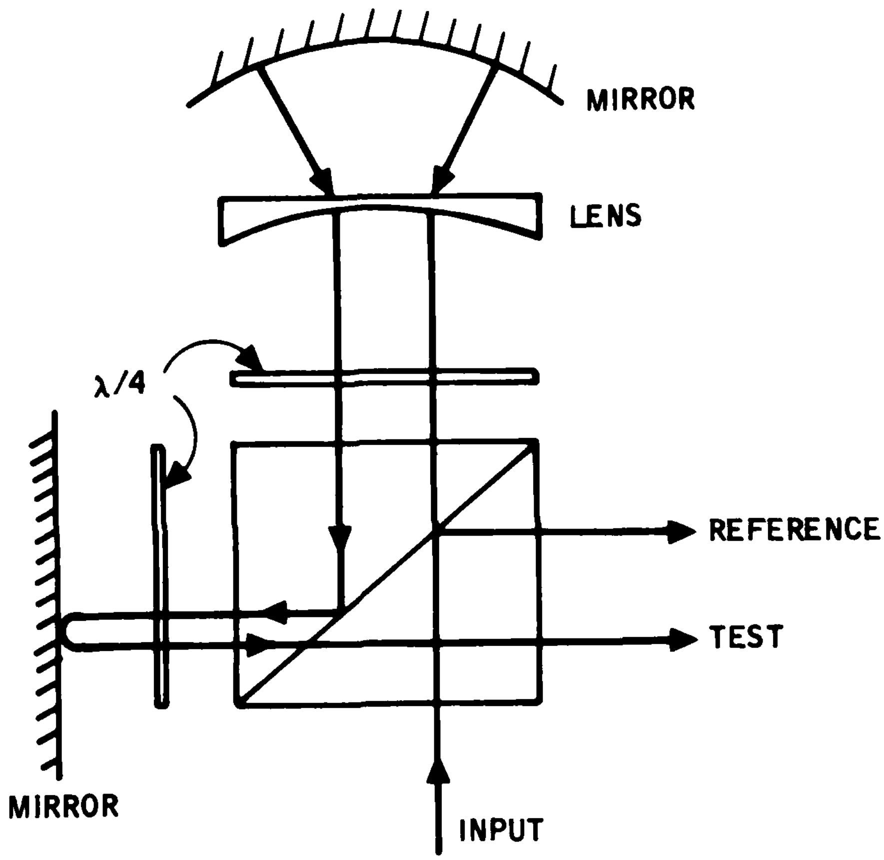


Figure 11. Double Pass Transmission Wavefront Distortion Test

Table III. Results of %MTF Measurements of Selected KBr Lenses

Specifications and Results for KBr Lenses

Sample No.	On Axis	Off Axis	Effective Focal Length	Flange Focal Length
Specification	>74%	>66%	67.8 ±.7mm	17.86 ±.25mm
Control*	75.48%		69.26	17.62
-018	77.29%	72.84%	67.23	17.76
-014	74.69%	71.04%	67.08	17.69
-038	74.98%	68.69%	67.16	17.71

*The control lens is a lens which had already been measured. The lens is #597 from the lenses developed by CMSC under DARPA contract DAAK 70-77-C-0218.

Lens Run Parameters

Sample No.	First Stage Parameters			Second Stage
	Shape	Ram Speed	Lubrication	Isostatic Pressure
-018	Cube	.03"/min	No Teflon	100 psi
-014	Cylinder	.03"/min	No Teflon	4K
-038	Cylinder	.8"/min*	No Teflon	4K

*This lens was first stage forged with a constant strain rate of ≈50%/min. Thus, as the run progressed, the ram speed was decreased.

An additional evaluation technique is necessary to verify that the radius of curvature of the concave surface is maintained within tolerance. A digital spherometer is being purchased for this need. This spherometer works by measuring sagitta of the lens with an accuracy of 40 millionths of an inch. The meter then directly calculates the radius of curvature from sagitta. This instrument is easy to operate and ideally suited to a production environment.

The present optical evaluation results imply that the refined forging parameters are significantly better than the original parameters for producing quality lenses.

1.4 EQUIPMENT DESIGN

Since the elimination of the 4,000 psi helium parameter from the second stage process (subsection 1.2.3), the overall equipment design problem has been greatly reduced. The remaining major piece of equipment design involves automating the forging press so that reproducable forgings can be made. It is extremely difficult to manually control a 350 ton press to move at .15 mm/min on a repeatable basis. An automated system will eliminate this problem. With an automated system, it will also be much easier to vary forging rate as an exponential decay in order to achieve constant strain rate (subsection 1.2.1). The preliminary design has been done, but equipment availability and compatibility may force changes in design. The forge automation will be described in detail after the major components arrive and are tested.

The first and second stage series dies have been designed (Figures 12 & 13) and are presently being fabricated. A possible design to allow the forging of the flange into the lens is being considered, but will not be attempted until some simple tests first show feasibility.

1.5 PROGRAM STATUS

The program schedule and milestones are shown in Figure 14. The following is a list of the current subtasks and notes describing where they are either completed or in progress. It should be noted that where the Process Optimization subtasks have been identified as complete, an acceptable solution has been found; but the parameters are constantly being re-evaluated for an optimum process.

Task 1.0 Process Optimization

This task is intended to optimize the procedures for the production of the KBr plano-convex lenses by the hot forge-to-shape process. At the time of this report, 60 forgings have been made for this purpose. All lenses produced since run 044 have produced high quality lenses which will be acceptable for use in the IR imager.

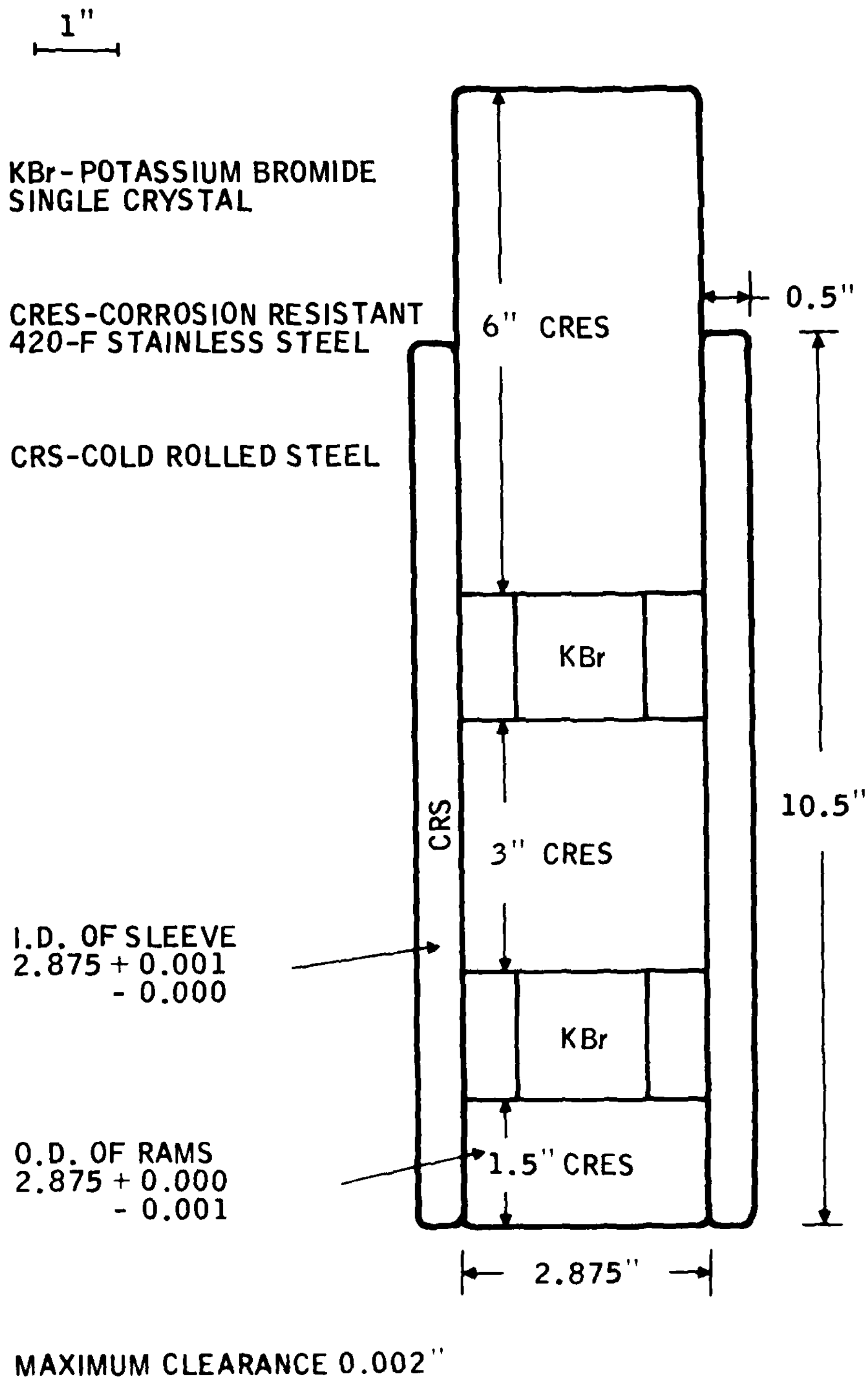


Figure 12. Die and Sleeve Set for First Stage Series Forging

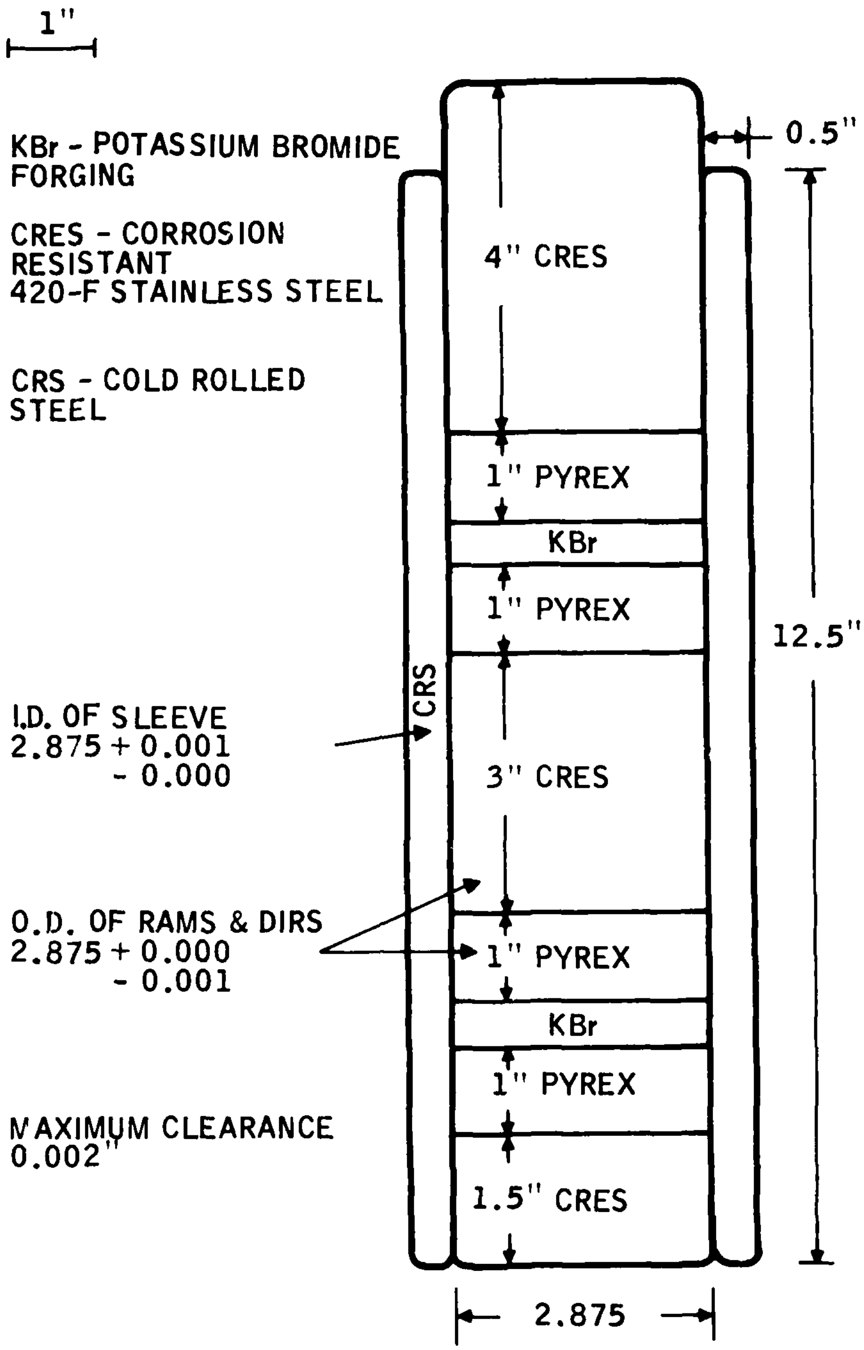


Figure 13. Die and Sleeve Set for Second Stage Series Forging

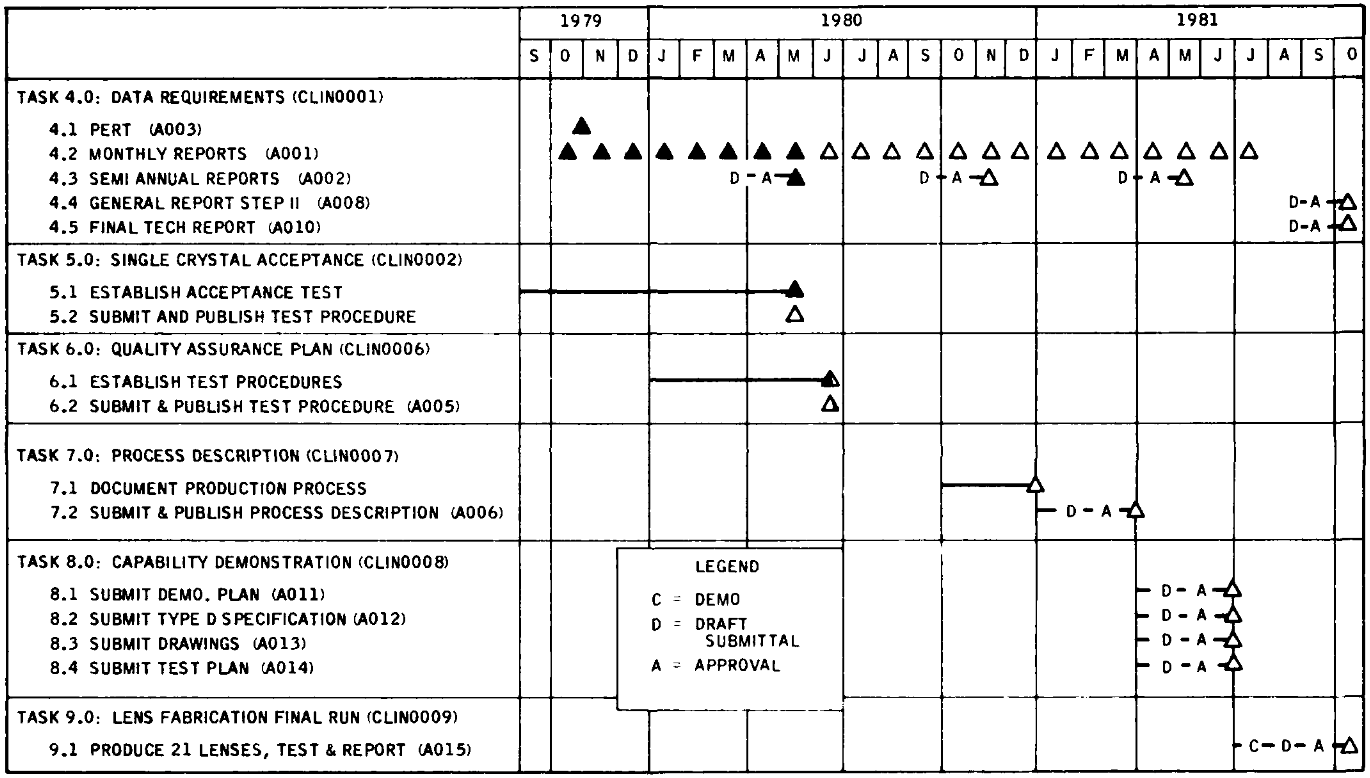


Figure 14. Program Schedule and Milestones

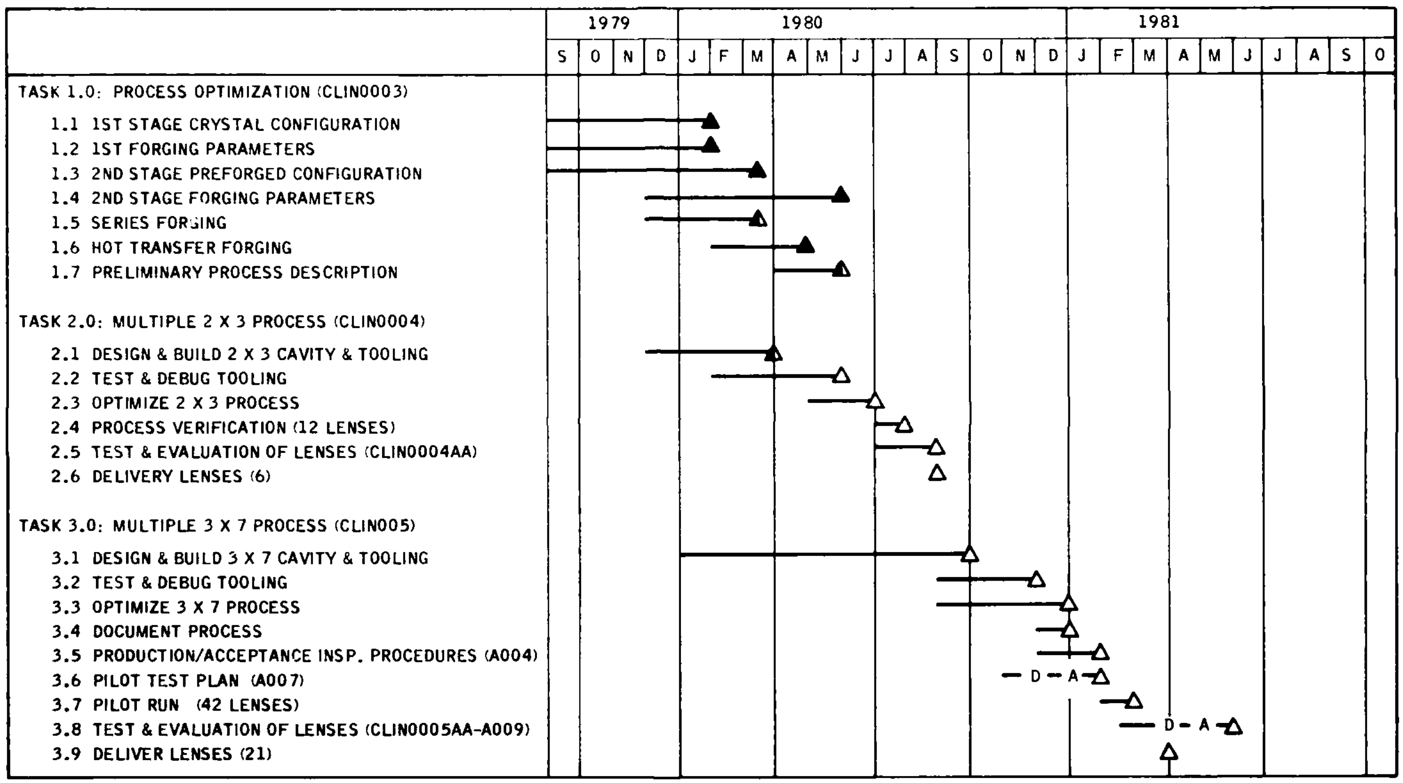


Figure 14. Program Schedule and Milestones (Concluded)

Sub-Task 1.1 First Stage Crystal Configuration (Completed)

A more cost effective KBr single crystal configuration has been achieved by optimizing the mass, shape, orientation and residual strain of the crystals obtained for the forged-to-shape process.

Sub-Task 1.2 First Stage Forging Parameters (Completed)

The first stage forging parameters have been optimized to give the best quality lenses while minimizing cost. The parameters studied include: temperature, lubrication, strain rate, sleeve and die materials and starting crystal preparation.

Sub-Task 1.3 Second Stage Pre-Forged Configuration (Completed)

The first stage forged-to-shape process has been optimized such that less starting material may be used. Also, the pre-machining step which originally preceeded second stage forging has been eliminated by using conical dies for the first stage forging.

Sub-Task 1.4 Second Stage Forging Parameters (Completed)

The second stage forging parameters have been optimized, while maintaining the quality of the forged lenses. The major result was the elimination of the 4,000 psi helium isostatic forging pressure. The removal of this constraint has drastically simplified the second stage tooling and forging process.

Sub-Task 1.5 Series Forging

The dies have been designed and are in fabrication. Present forging experience leads one to expect this to be a straightforward problem.

Sub-Task 1.6 Hot Transfer Forging

The ability to unload hot first stage dies has been successfully demonstrated. The loading of a preheated crystal into hot dies is being investigated for the first stage process. The hot transfer technique for the second stage process has not been tried but it appears to be a much more difficult problem.

Sub-Task 1.7 Preliminary Process Description

The process parameters have been defined, and a step-by-step process description is currently being compiled.

Task 2.0 Multiple 2x3 Process

Sub-Task 2.1 Design/Build 2x3 Tooling

The first and second stage 2x3 dies have been designed. Tooling will commence as soon as the results of the series forging is completed.

Sub-Task 2.2 Text/Debug Tooling

Inactive.

Sub-Task 2.3 Optimize 2x3 Process

Inactive.

Sub-Task 2.4 Process Verification

Inactive.

Sub-Task 2.5 Lens Test and Evaluation

Several lenses have been taken to NV&EOL for %MTF measurements (Table 3). Considerable effort has been made to develop a production technique to verify lens quality. The main candidate at this time is the Shearing Interferometer Technique. Presently, polariscope, Twyman-Green, and Double Pass Interferometer Techniques are used to characterize the lens quality.

Sub-Task 2.6 Delivery of Lenses

Inactive.

Task 3.0 Multiple 3x7 Process

All items in this task are inactive at this time.

Task 4.0 Data Requirements

Sub-Task 4.1 Program Evaluation and Review Technique (Pert)

Pert chart generated and delivered.

Sub-Task 4.2 Monthly Reports

All monthly reports prior to this report have been submitted.

Sub-Task 4.3 Semiannual Reports

This report covers the initial period of 7 September, 1979 to 7 April, 1980.

Sub-Task 4.4 General Report Step II

Inactive.

Task 5.0 Single Crystal Acceptance

Sub-Task 5.1 Establish Acceptance Test

A routime technique has been determined to inspect incoming crystals.

Sub-Task 5.2 Submit and Publish Test Procedure

Documentation of the acceptance test is presently being written.

Task 6.0 Quality Assurance Plan

Sub-Task 6.1 Test Procedures

Throughout the process-refinement, several techniques were developed to maintain the quality assurance of the final lenses. There is a distinct trade off to the use of test procedures. Test procedures generally increase the required handling of the lens during production. A careful consideration is needed to determine the best trade off between quality assurance and the potential surface damage to the forgings due to testing.

Sub-Task 6.2 Submit and Publish Quality Plan

Inactive.

Task 7.0 <u>Process Description</u>

All sub-tasks in this task are inactive at this time.

Task 8.0 <u>Capability Demonstration</u>

All sub-tasks in this task are inactive at this time.

Task 9.0 <u>Lens Fabrication Final Run</u>

Inactive.

SECTION II
CONCLUSIONS

The MM&T program for the production of hot forged-to-share KBr lenses is logically divided into three problem areas: refinement of the process, the generation of evaluation techniques, and equipment design. Of these three areas, the process refinement has been the most critical in the initial stages of the program. At this time a "best" process has been defined and the focus of the effort has shifted to the two remaining areas. The success in simplifying the process and the ability of avoiding needless equipment design, more than justifies the labor involved in refining the forging process. Although the present set of process parameters are not necessarily ideal, the evaluation and equipment design are geared to those values. As new data is analyzed any change in process parameters which will aid equipment design and final production will be implemented. Since the present process generates very acceptable lenses, the major consideration in changing parameters will now be to lower cost or increase productivity.

Lens evaluation techniques show considerable improvement in the present lenses as compared to earlier forgings. The %MTF data imply that the KBr lenses qualify extremely well for their function in the SU-103/UA imager.

Equipment design is now the major emphasis of the program, with automation of the forge as the major task. Considerable simplification of equipment design has occurred as a result of refining the forging parameters.

SECTION III
PROGRAM FOR NEXT INTERVAL

The emphasis for the next six months of the program will be the completion of the optical evaluation techniques and the development of the automated equipment needed for lens production. The optical evaluation techniques will involve the development and the use of several standard optical techniques to determine final lens quality.

The equipment design will mainly center around the automation of the forging press. In addition, the series dies will be optimized and the possibility of new dies to forge in lens flanges will be examined.

During the next six months the following deliverables will be produced:

- Preliminary Process Description.
- Delivery of 6 Lenses from 2x3 Process.
- Publish the Single Crystal Test Procedure.
- Publish the Quality Assurance Test Procedure.

SECTION IV
PUBLICATION AND REPORTS

No reports, talks, or publications were made on the work associated with this program during the current reporting period.

SECTION V
IDENTIFICATION OF PERSONNEL

During the first part of this program the following personnel worked the indicated hours in their areas of responsibility.

Individual	Responsibility	Hours
Roger Anderson	Forging Development and Process Transfer	250
Regis Betsch	Overall Engineering Design and Process Development	340
Earl Burandt	Production Techniques	6
William Harrison	Program Manager	376
Gil Hendrickson	Overall Engineering Design and Process Development	652
Joseph Koteles	Quality Control	7
Rod Luhmann	Optical Polishing, Technician	695
Maurice Murphy	Mechanical Fabrication Techniques	37
Clark Olson	Second Stage Forging, Technician	562
Walt Polgrin	Second Stage Forging, Technician	133
Maynard Sandberg	First Stage Forging, Technician	759
Fran Schmit	Optical Evaluation	169
Joseph Starling	Initial Transfer of Forging Process	169

During the first six months of the program three personnel changes have occurred. Two people have left the program, Joseph Starling and Gil Hendrickson. A new addition, Dr. Regis Betsch, joined the optics group in January, 1980.

RESUMES

The resumes presented on the following pages introduce our program personnel.

ROGER H. ANDERSON

Job Title: Senior Research Scientist

Formal Education: BS, Metallurgical Engineering (1968), University of Minnesota

Work Experience: Mr. Anderson has been working for Honeywell since 1958. Recently he pioneered the development of the isostatic press forging approach to fabricate strengthened, fine-grained alkali halides or alkaline earth fluorides and to produce halide optical elements that require no further surface preparation. In 1978 a forged KBr lens successfully passed the optical requirement for a FLIR imager.

In 1968, Mr. Anderson started working with magnetically soft ferrites. The processing involved both sintering and hot-pressing of these materials. In 1971 he began work to demonstrate that alkali halide single crystals can be strengthened by a number of deformation processes. He has shown that these materials can be extruded, rolled, hot forged, forged with constraint, and isostatically forged.

Prior to joining Honeywell in 1958, Mr. Anderson had gained broad experience in conventional machining methods as a model maker and shop supervisor. His initial work at Honeywell involved strengthening of beryllium by alloying and dispersions using powder metallurgy techniques. An outgrowth of this work was the development of a diffusion welding process for the beryllium Electrostatic Gyro.

Significant Papers and Patents:

Mr. Anderson is the coauthor of nine technical papers on alkali halide crystal characterization and forging techniques, and has been granted two patents related to the forging of alkali halide materials.

R. J. BETSCH

Job Title: Senior Development Engineer

Formal Education: BS, Physics, Pennsylvania State University
BS, Mathematics, Pennsylvania State University
PhD, Solid State Science, Pennsylvania State University

Work Experience: Dr. Betsch is presently developing improved techniques for hot-forging-to-shape alkali-halide lenses. He has 7 years of previous experience at the Materials Research Lab at Pennsylvania State University. Between 1972 and 1979 his studies include materials selection for 10.6 μm laser windows, optical characterization techniques for materials analysis, and development of a temperature-compensatable material for Surface Acoustic Wave (SAW) devices. This work included extensive material synthesis and characterization and a considerable amount of equipment design and development using computer control and analysis programs.

Significant Papers:

"Characterization, Synthesis, Growth and Characterization of Potential 10.6 Micron Window Materials," Final Report for the period 1971-1974, Air Force Cambridge Research Laboratories Contract No. AFCRL-TR-74-0618. W. B. White, Principal Investigator.

"Structural Characterization of Minerals by Raman Spectroscopy," Quarterly Reports and 1st through 5th Annual Reports, 1974-78, National Science Foundation Grants; GA-40240, EAR 73-00243 A01, and EAR 77-15181. W. B. White Principal Investigator.

Betsch, R.J. and White, W.B., "Vibrational Spectra of Bismuth Oxide and the Sillenite-structure Bismuth Oxide Derivatives," Spec. Chem Acta. 34A, 504-514 (1978)

Betsch, R.J. and White, W.B., "High-Pressure Intensifier for Oxygen use to 4 Kilobars," Rev. Sci, Instrum., 45, No. 8 (1974), 990-991.

Betsch, R.J., Park, H.L., and White, W.B., "Raman Spectra of Stoichiometric and Nonstoichiometric Rutile," Mat. Res. Bul., (pending).

Betsch, R.J. and Johnson, G.G., "Bridging the Hardware/Software Gap in System Control:, ASTM publication of the Symposium on Computer Automation of Materials Testing, ASTM STP 710, 1980 pp 11-25.

W. B. HARRISON

Job Title: Supervisor, Optical Development

Formal Education: BS, Ceramic Engineering, Virginia Polytechnical Institute
MS, Ceramic Engineering, Virginia Polytechnical Institute

Work Experience: Mr. Harrison is presently Program Manager of several DoD contracts on halide materials processing and coating for IR optics and laser windows. In these programs, manufacturing methods and techniques are being developed to produce hot-forge-to-shape and optical-finish IR lenses of KBr and other alkali halides. Large, high-strength alkali-halide windows for high-power CO_2 lasers have also been developed by the use of three basic strengthening approaches: recrystallization; a solid solution alloying; and the dual process of alloying and recrystallization. Using these approaches, alloyed alkali-halide material with yield strengths greater than 6000 psi have been produced. Mr. Harrison has organized the Ceramic Center's optical quality of halide windows. In conjunction with S&RC he has developed AR coatings for these materials which have low absorption and provide moisture protection to the alkali halides.

Since joining the Honeywell Research Center in 1959, Mr. Harrison has been engaged in a number of projects. He became Chief Investigator of the AROD-sponsored project "Mechanical Behavior of Polycrystalline Ceramics" in 1960 and continued this program until 1965. During his 21 years at Honeywell, he has studied in a wide variety of electrical and mechanical characteristics of pure oxide and piezoelectric ceramics as achieved by sintering and hot-pressing. He has coordinated Honeywell's input to the Naval Ship

Systems Command to help establish MIL-STD-1376 (Ships) 21 December 1971 for piezoelectric ceramics.

He has 8 years of prior experience in ceramics with Allis Chalmers, Hercules Powder Co., and VPI. In 1951 he worked as a Research Fellow on lightweight refractory radomes at the VPI Engineering Experiment Station. Also in 1951 he was a quality control shift supervisor for Hercules Powder Co. From 1952 to 1959 he was employed by the Allis Chalmers Manufacturing Research Laboratories where he set up ceramic research facilities.

Significant Papers:

"Influence of Surface Conditions on the Strength of Polycrystalline MgO," J. Am. Ceramic Society, 47, No. 22, p. 573 (1964).

"Mechanical Behavior of Polycrystalline Ceramics," Final Report, AROD Contract DA-11-022-ORD-3441, April 1965.

"Unconventional Processes for Fabricating Ceramics," Final Report, Sandia Contract 58-4450, November 1969.

"Halide Materials Processing for High-Power Infrared Laser Windows," AFCRL-TR-73-0372(11) Special Reports, No. 162, 19 June 1973, Conference on High-Power Infrared Laser Window Materials, p. 391, October 1972.

"Mechanical and Optical Properties of Recrystallized Alkali-Halide Alloys," AFCRL-TR-74-0095(11) Special Reports, No. 174, 14 February 1974, Third Conference on High-Power Infrared Laser Window Materials, p. 615, November 1973.

"The Growth, Characterization and Recrystallization of Alkali-Halide Alloyed and Doped KCl," Proc. 4th Conf. on Infrared Laser Window Materials, p. 599, January 1975.

E. F. E. BURANDT

Job Title: Production Engineering Supervisor

Formal Education: Dunwoody Industrial Institute, 1951, Electronics
Undergraduate study, University of Minnesota
Extension Program

Work Experience: Mr. Burandt is presently in charge of the production engineering group at the Honeywell Ceramics Center, which is responsible for all ceramic production programs including detailing layouts, cost reduction studies, costing, tooling and maintaining the uniform quality of product flow from this department. Active high volume programs include the MK 46 high power transducer, Pair hydrophone, Rockeye power supply and many Sandia MC items.

He has been with the Honeywell Ceramics group for 24 years, where he has worked with all aspects of piezoelectric materials and piece-part development and production. This includes new composition development and evaluation, study of process variation effects on ceramic properties, writing of complete process description, evaluation of cost effects using new processes and methods, new product costing, process development, and production of Sandia MC items. A lead production engineer on the MK 46 piezoelectric ceramic element, he was directly responsible for the development and mass production of this item (more than a half million elements). He was also involved in the automation of the Rockeye piezoelectric power source, which has been produced in quantities greater than 20 million at the rate of up to 450,000 per month; and in the process description and equipment procurement for the TR-155 program.

G. O. HENDRICKSON

Job Title: Senior Materials Engineer

Formal Education: BS, Metallurgical Engineering, Michigan Technological University, 1957.

Work Experience: Mr. Hendrickson joined the development engineering staff of the Ceramics Center in June 1972 and is currently investigating machining, hot forging and thermal processing of halide crystals for high power laser windows.

He transferred to the center from the Honeywell Aerospace Division, where for 12 years in the Materials and Process (M&P) Engineering Section he worked on the application of ceramic-to-metal, glass-to-metal and anodic bonding to aerospace hardware. During this time, he was assigned to a consulting specialty in both nondestructive testing and experimental stress analysis.

Included in Mr. Hendrickson's prior assignments as a materials and process applications engineer were: (1) design and production engineering support on numerous aerospace programs, (2) specialist in module interconnect welding fabrication, (3) establishment of a failure analysis laboratory and directing mechanical and metallurgical analysis and (4) specialist in experimental stress analysis and electronic module welding process development.

Before joining Honeywell, Mr. Hendrickson worked for Marquette Manufacturing Co. as a laboratory development metallurgist with primary responsibility for developing flux coatings for welding electrodes. He assisted in training sales personnel and resolving customer technical problems.

Significant Papers:

A list of Mr. Hendrickson's publication related to laser window technology is available upon request.

J. J. KOTELES

Job Title: Senior Quality Engineer

Formal Education: BS, Mechanical Engineering, Michigan Technological University, 1965
Numerous Honeywell on- and after-hour courses.

Work Experience: Mr. Koteles joined the Quality staff of the Ceramics Center during July 1979. In his present assignment, he has the responsibility for directing and coordinating the Quality Engineering activities for both development and production programs.

Mr. Koteles has been with Honeywell Inc. for over 17 years, having joined the organization in 1962. His initial position was as a design engineer on non-floated gyros. After two years in this capacity, he transferred to the Reliability Engineering group to support gyro design and production. In 1968, Mr. Koteles became a part of the Quality Department and has worked as a Quality Engineer since that time. As a Quality Engineer, he has been associated with inertial-type components, aircraft instruments such as height indicators, and full gage systems, the manufacture of mechanical piece-parts, and the main engine controller for the Space Shuttle program.

Prior to his coming to Honeywell, Mr. Koteles was employed as a Design Engineer with both the Dresser Crane Co., and Lear-Siegler, Inc.

MAURICE P. MURPHY

Job Title: Associate Development Engineer

Formal Education: BS, Business Administration, University of Minnesota

Work Experience: Mr. Murphy has spent 23 years at Honeywell as a research and development technician, with background in fabricating and testing various materials, including piezoelectrics, Yttium Oxide, Stabilized Zirconia, powdered metallurgical fabricating and compositional study. His experience also includes refractory oxide materials as related to crystal structure and its influence of room temperature and elevated temperature flexure strengths.

FRANCIS M. SCHMIT

Job Title: Senior Research Scientist

Formal Education: BS, Physics, St. Cloud State (1961)

Work Experience: Mr. Schmit's present work assignment focuses on optical testing of hot forged alkali halide lenses. This includes testing and evaluating all lenses forged in our facility as well as evaluating experimental optical test techniques applicable to our process. These evaluations are all correlated to actual MTF data to guarantee accuracy.

Accomplishments prior to 1978 were in holographic wide-band data recording. This employed a thermoplastic-photoconductor system as the storage medium. Mr. Schmit was the principal investigator on the RADC supported phase of that effort, receiving a letter of appreciation from the contract monitor dated Nov. 1977. Specific contributions to this project were in the areas of holography, electrostatic charging, pneumatics, thermodynamics and mechanics.

A magneto-optic material (MnBi) was the focus of his efforts up to 1974. This material was used for bit-serial data storage in an erasable medium for an optical mass memory system. Working capabilities in laser physics, pneumatics and vacuum deposition technology were demonstrated on this project.

Very early work included impurity diffusion into semiconductors, chiefly silicon.

Significant Papers:

"A KD_2PO_4 Light Beam Deflector," with T.C.Lee and J.D. Heaps, Proceedings of IEEE, Vol. 56, No. 9, Sept. 1968.

"Optical Mass Memory Experiments on Thin Films of MnBi," with R.L. Aagard, D. Chen, R. Honebrink, and G.N. Otto, IEEE Transactions on Magnetics, Vol. MAG-4, No. 3, Sept. 1968.

"Experimental Evaluation of MnBi Optical Memory System," with R.L. Aagard, W. Walters, and D. Chen, IEEE Transactions on Magnetics, Vol. MAG-7, No. 3, Sept. 1971.

"MnBi Films for Magneto-Optic Recording," with D. Chen and G.N. Otto, IEEE Transactions on Magnetics, Vol. MAG-9, No. 2.

"Observations of Repeated Curie Point Writing Effects on MnBi Films," IEEE Transactions on Magnetics, Vol. MAG-9, No. 3, Sept. 1973.

"Thermoplastic-photoconductor Tape Development for Holographic Recording Applications," with T.C. Lee, N. Marzwell, and O. Tufte, presented at the 1977 conference of Laser Engineering and Applications, June 1977.

"Performance of the Thermoplastic-photoconductor Tape in Holographic Recording," with T.C. Lee, N. Marzwell, and O.N. Tufte, EO Systems Design Conference, Anaheim, Californis, Oct. 1977.

"Development of Thermoplastic-photoconductor Tape for Optical Recording," with T.C. Lee, N. Marzwell, and O.N. Tufte, Applied Optics, August 1978.

"Developments in Thermoplastic Tape for Optical Recording," with T. C. Lee, SPIE Proceedings, Vol. 177, pp. 88-96, April 1979.

Patents:

"Semiconductor Method and Apparatus," No. 3,459,668.

"Optical Mass Memory," No. 3,631,415.

"Magneto-optic Readout System," No. 3,705,395.

"Optical Mass Memory," No. 3,715,740.

"Optical Memory with Readout Beam Anneal," No. 3,815,151.

"Optical Memory with Improved Signal to Noise Ratio," No. 3,869,193.

JOSEPH E. STARLING

Job Title: Development Engineer

Formal Education: BS, Ceramic Engineering, University of Missouri-Rolla, 1967
MS, Ceramic Engineering, University of Missouri-Rolla, 1971

Work Experience: Mr. Starling has been assigned to the alkali halide infrared laser window program during his four years at Honeywell. He is responsible for the hot-forging recrystallization studies on such halides as NaCl, KCl, KBr and their alloys. Included in his tasks are microstructural analysis, finishing, optical polishing and mechanical strength behavior of these as well as other ceramic materials.

At the University of Missouri-Rolla, he was a PPG Fellow. His graduate study included work on stress-gradient biased diffusion of alkali ions in glasses. He was previously employed as an engineer in the R&D department of Chicago Vitreous Corp., where his work included thermally insulating enamels, and enamels with specific electrical properties.

Mr. Starling is a member of the American Ceramic Society, Keramos (Ceramic Engineering Professional Fraternity), and Tau Beta Pi.

Significant Papers: A list of Mr. Starling's publications is available on request.

APPENDIX A

DISTRIBUTION LIST

DISTRIBUTION LIST

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Development and Readiness Command ATTN: DRCMT (Mr. Fred Michel) 5001 Eisenhower Avenue Alexandria, VA 22333	1
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